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ABSTRACT

The paper describes the design and construction history of a 10-story (with provision for two more stories) combination parking structure and office building cost effectively built over soft clay in Chicago, Illinois. The site profile consisting of medium dense to dense sand and sandy silt underlain by soft compressible clay to a very thin, sometimes non-existent, very stiff to hard clay layer underlain by water bearing very dense sandy silt to limestone bedrock made foundation design within the owner's budget difficult.

The development of a unique combination of strip footings in the shallow, medium dense to dense sand layer combined with straight shaft piers under the columns and extended to the very dense sandy silt layer is described. The instrumentation program to determine the load distribution between strip footing and straight shaft pier is presented as well as the instrumentation monitoring during construction and for several years after construction. Observed settlement and load distribution is compared favorably to predicted settlement and load distribution.

INTRODUCTION

Chicago perhaps more than any other city has stood as a full-scale laboratory where innovation in foundation engineering has continued since the nineteenth century. Following the great Chicago fire of 1871, architects and engineers vied to build ever taller and heavier structures without the benefit of modern soil mechanics. Most structures built until 1895 were founded on spread footing foundations supported over Chicago's soft compressible clay deposit even though building heights reached 21 stories. Peck (1948) describes how differential settlements of as much as 23 inches were measured within the Auditorium Building, which still stands today. Prior to 1880, spread footings were not even proportioned to achieve equal soil bearing pressures throughout a building. Footing bearing pressures as high as 15,000 pounds per square foot (720 kPa) were reported.

By about 1905, most Chicago buildings with heights greater than 6 stories were founded on deep foundations consisting mostly of driven timber piles to "hardpan" or hand-dug caissons to hardpan or rock. The move to deep foundations was caused by the slow realization that settlements were excessive and by the sudden need to underpin many footing supported structures which were adjacent to freight tunnels dug 50 feet (15 meters) below City streets in 1904.

With the development of consolidation theory by Terzaghi in 1925, reliable predictions of shallow footing settlement over soft Chicago clay were possible. Peck, et al (1955) compared the measured settlement of several early Chicago structures on shallow foundations with the modern settlement estimates with good agreement. But by this time, the use of presumptive pressures and experience resulted in most footing supported buildings throughout Chicago neighborhoods being limited to a height of three stories.

PRESSUREMETER TESTING IN CHICAGO

Innovations in Chicago's deep foundation practice since World War II are described by Baker, et al (1998). One of these innovations has been the use of the Menard pressuremeter for maximizing foundation bearing pressures and predicting settlement, particularly in over-consolidated soils. With the pressuremeter test, the allowable bearing pressure for deep caisson foundations resting on Chicago hardpan or very dense silt under hardpan, has steadily risen from a code-allowable value of 12 kips per square foot (575 kPa) to as high as 60 ksf (2875 kPa). With improved settlement prediction in comparison to consolidation tests, engineers have been able to support portions of buildings on differing soils -- such as building cores to rock and perimeter caissons on hardpan -- to the economic benefit of the building owners. Today, in-situ pressuremeter tests are required by the updated Chicago building code where caisson foundation bearing pressures exceed 20 ksf (960 kPa). An example of the use of the pressuremeter test for settlement prediction in a mixed foundation design is given by Baker (1993).

SOUTH CHICAGO FOUNDATION DESIGN

The south side of Chicago extending from about Roosevelt Road (12th Street) to 22nd Street and the Lake Michigan shore to the Chicago River contains a particularly challenging portion of the City's geology. In this area, the soft Chicago clay is often very soft with water contents typically exceeding 30% and often nearing the liquid limit at about 45%. The area is characterized by shallower bedrock and thin, variable and weak, or non-existent hardpan. Peck (1954) also describes several buried stream channels which extend through the area. Within the buried stream channels, partly organic soils have filled in deep ravines which were eroded into the glacial clay during the time when Lake Michigan was about 80 feet (24.4 meters) lower than today.

Despite these challenges, this area of Chicago is experiencing some of the most rapid growth in the City. Current practice is to support three-story town home structures on shallow foundations and higher buildings on deep foundations. Some of these town homes are supported on dynamically compacted fill over the very soft clay and others are supported within unimproved fill on heavily reinforced structural box foundations at reduced bearing pressures. A single six-story structure, the Senior Suites at 14th and Indiana is supported on a shallow heavily reinforced grade beam grid foundation with only a three-foot crawl-space excavation to compensate for building load and reduce long term settlement.

AN INNOVATIVE MIXED FOUNDATION DESIGN

Engineers recently designed an innovative mixed foundation to support a 12-story combination parking structure and office building on the south side of Chicago. The design concept was to use a limited number of highly stressed, end-bearing caissons to reduce settlement of a strip footing foundation system. Since this approach involved combining shallow and deep foundation systems on normally consolidated and over-consolidated soils, it was essential to be able to predict how the different systems would perform together.

Construction of 10 stories (with provision for two more stories) of the building was completed in 1996 at 1911 South Indiana Avenue in Chicago, Illinois. The structure is of reinforced concrete design with 24 x 40 foot (7.3 x 12.2 m) bays. The lower floor levels are parking and upper floor levels are office space. The lowest floor over half of the structure is at grade with the other half depressed approximately 4 feet (1.2 m). Initial construction was 10 stories with two additional floors to be added at a later date as the need arises. Maximum design column loads are 2,700 kips (12 MN).

The soil profile at the site consists of medium dense to dense sand and sandy silt to a depth of approximately 16 feet (4.9 m) followed by a stiff clayey crust underlain by soft compressible clay. The soft compressible clay gradually increases in strength to stiff and extends to a depth of approximately 65 feet (19.8 m) where a thin (sometimes non-existent) very stiff to hard silty clay layer exists underlain by layers of dense to very dense water-bearing sandy silt to limestone bedrock at 90 feet (27.4 m). Because of the potential for squeezing of the soft clay and the relative thinness of an adequate bearing layer at depth, a preliminary geotechnical report prepared for the site recommended against the use of conventional belled caissons for this project as too risky and expensive.

STS Consultants, Ltd. was retained to further evaluate a shallow foundation solution and provide cost effective methods for reducing the anticipated settlement. A supplementary field exploration program was performed consisting of five (5) borings including in-situ pressuremeter tests conducted within the upper sand just below anticipated footing level, pressuremeter testing within the lower sandy silt just below the potential deep caisson bearing level, in-situ vane shear testing within the soft clay below footing level, selective, undisturbed 3-inch (75 mm) diameter piston sampling of soft clay for consolidation testing, and measurement of the shallow and deep water table levels. Geotechnical parameters for the site are summarized in Fig. 1.

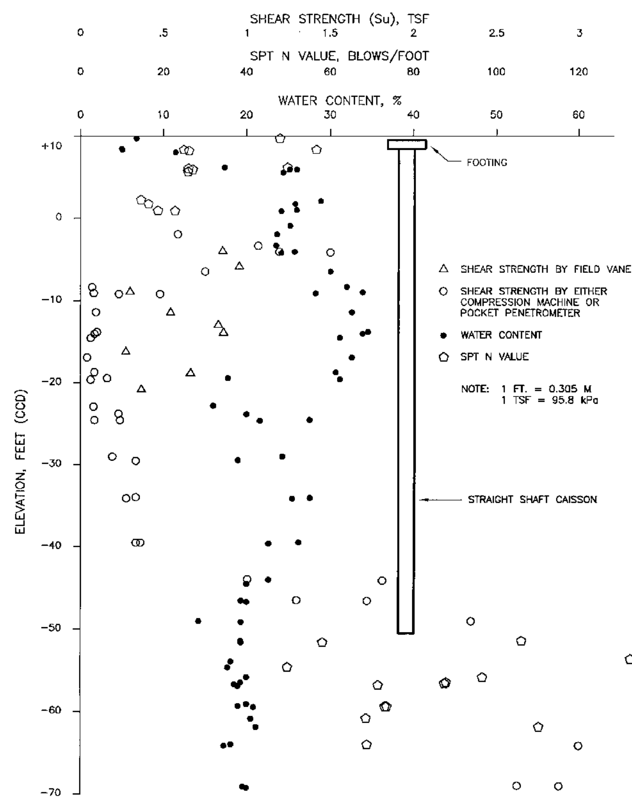

Fig. 1. Shear strength, SPT N value, and water content versus elevation at 1911 South Indiana.

Shallow Foundation Analysis

Because of the presence of the over-consolidated upper dense sand layer and stiff clay crust, strip footings were a possibility for support of the structure as they act in effect like a mat when combined with the dense sand layer. Because of the stress spreading effect of the dense sand and stiff clay layer, the actual contact bearing pressure design of the footings has little influence on the ultimate settlement since it is the average stress increase in the underlying soft clay resulting from the total weight of the building that causes the settlement. Calculated maximum settlement for this equivalent mat case was eight inches (20 cm) with two to three inches (2.5 to 7.5 cm) occurring during construction and five to six inches (12.5 to 15 cm) thereafter. This was considered excessive and ruled out shallow foundation only solutions.

Deep Foundation Analysis

Installation of conventional belled caissons on the thin, hard silty clay or dense, water bearing silt was not considered due to the concern that water infiltration would prevent conventional belled caisson construction. The cost of using deep filtered dewatering wells to lower the pressure head in the silt (as has been done on a handful of other projects in Chicago) exceeded the project budget.

Various other deep foundation solutions were considered including rock-socketed caissons, piles (driven steel and auger-cast), and straight-shaft caissons to top of rock, but cost estimates on all conventional solutions were also outside of the project budget.

Combination System Analysis

To take advantage of the lower cost of the strip footing solution, while trying to reduce the settlement to an acceptable range, a combination system was designed. The combination consisted of 14-foot (4.3 m) wide continuous strip footings supported on the near surface dense sand layer and five to six-foot (1.5 to 1.8 m) diameter straight-shaft caissons extended down to the dense water-bearing sand and silt layer. It was anticipated that the straight shafts could be excavated and quickly filled with concrete before water seepage became a problem (not possible for belled caissons).

The design contemplated approximately 60% of the building load being initially supported by the strip footings with 40% carried by the straight shafts with this ratio reversing with long-term consolidation of the soft clay reacting to the strip footing pressures. The combination of strip footings and straight-shaft caissons reduced the estimated settlement to less than one-third that predicted for the strip footing or mat foundation solution alone. Since the straight shafts were considered primarily as settlement reducers, a higher than normal bearing pressure could be accepted consistent with the desired settlement limitation. The design approach was relatively unique in the sense that the settlement reducing elements carried the load primarily in end-bearing rather than in side friction, which is the common system where a mat supported on settlement reducing piles is normally utilized.

The strip footings were designed structurally to withstand a range of soil pressures up to 4500 psf (215 kPa) since it was not possible to guarantee the exact load distribution between footing and shaft, particularly with time, as the underlying soft clay consolidated. Ultimate projected settlement for the combination system was in the range of two to three inches (5 to 7.5 cm) compared to eight inches (20 cm) for the strip footings only. The settlement reducing elements were designed to have a structural factor of safety of at least two (2) at the point of calculated soil failure and a soil factor of safety greater than one assuming all the load was taken by the settlement reducer. Modulus values measured in the pressuremeter tests in the dense silt were averaged and divided by a factor of two to compute the shaft tip settlement. This was done due to concerns that water infiltration and disturbance due to augering could loosen the silt at the base of the shaft excavation.

INSTRUMENTATION PROGRAM

To determine how load actually gets distributed into the ground, strain gages were placed in two representative shafts and first floor columns. Column B-6 was at the end of a strip footing and consisted of a 16 x 36 inch (41 x 91 cm) column over a 5-foot (1.5 m) diameter shaft. Column C-2 was an interior column and was 16 x 48 inches (41 x 122 cm) over a 6-foot (1.8 m) diameter shaft. In both cases, column concrete compressive strength was 8000 psi (55 MPa) and caisson concrete strength was 4000 psi (27.6 MPa). The strain gages monitored the load sharing between the shafts and the strip footings. The soil profile, foundation schematic and instrumentation are shown in Fig. 2.

Strain gage data for both the columns and the caisson shafts taken over a 3-1/2 year period are shown in Figs. 3 through 6. The strain gage data on the columns was relatively consistent and similar whereas the strain gage data in the caisson shafts differed drastically from one side of the shaft to the other indicating possible bending. However, the average values appear consistent and reasonable. The initial tension readings could be due to shrinkage of the concrete in the shaft being restrained by the large overlying strip footing to which the shafts were connected while cement hydration was undoubtedly still occurring.

It is also interesting to note that there has been little load increase since the building was completed in early 1996. The small load increase noted may be due to live load changes or possibly due to small concrete creep. Measured settlements have also been very small since completion of the building with a total measured settlement ranging from one inch

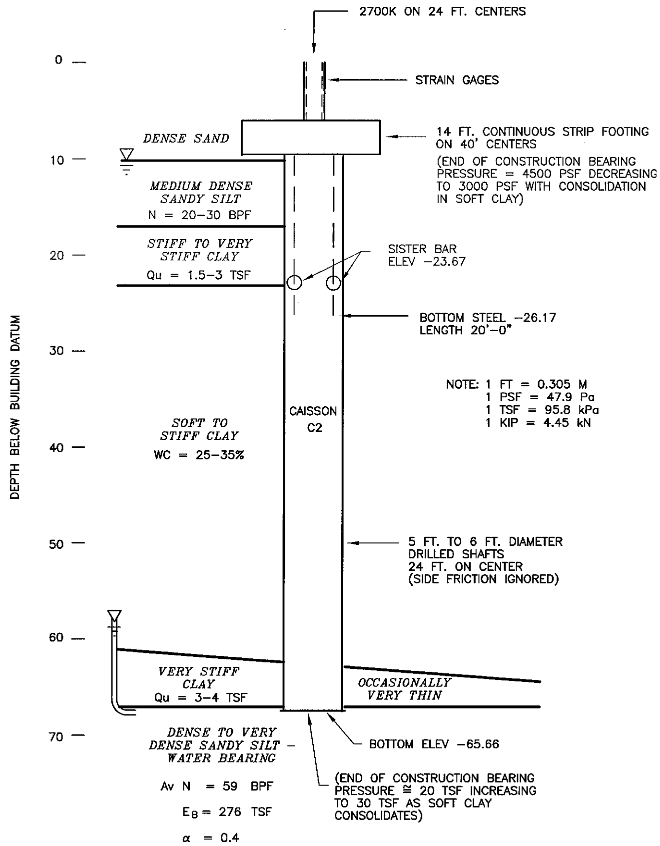

Fig. 2. Soil profile, combined strip footing and drilled shaft foundation, and instrumentation

(25 mm) at Column C-2 to 1-1/4 inches (32 mm) at Column B-6. Column B-6 also has the greatest percentage of the load carried by the caisson shaft as compared to the strip footing. This is probably due to the fact that the Column B-6 is at the end of the footing and does not get the same stress spreading influence that the massive footing provides for interior columns. The B-6 caisson appears to be carrying 76% of the column load whereas the C-2 caisson appears to be carrying 59% of the column load. It should be noted that the structure was designed for two additional floors so the current loading is only approximately 83% of the ultimate design loading. A summary of the instrumentation results is shown in Table 1.

Table 1. Measured Column/Caisson Load Distributions as of April 14, 1998.

Column Number	Calculated Column Load (kips)	Calculated Shaft Load (kips)	Calculated Shaft Base Pressure (ksf)	Measured Settlement (inches)
B-6	1978	1496	76	1.25
C-2	2327	1377	48	0.9

(Note: 1 kip = 4.45 kN, 1 ksf = 47.9 kPa, and 1 inch = 25.4 mm)

DATE	SETT. (in)	CHANGE IN MICROSTRAINS GAGE BLACK-1	GAGE GREY-1	GAGE AVERAGE	CONSTRUCTION ACTIVITY
19-Nov-94		0	0	0	Before column was poured
30-Nov-94	0.00	9	-15	-3	After column was poured
11-May-95	-0.63	-275	-249	-262	Eight floors poured
19-May-95		-318	-282	-300	Starting to form 9th floor
18-Jul-95		-505	-419	-462	Precast installed
26-Sep-95	-1.00	-556	-478	-517	Windows installed
14-Mar-96	-1.00	-568	-486	-527	Building completed
19-Aug-96	-1.00	-656	-575	-616	Building completed
21-May-97	-1.00	-705	-615	-660	Building completed
6-Nov-97	-1.12	-720	-614	-667	Building completed
14-Apr-98	-1.14	-735	-639	-687	Building completed

Note: 1 inch = 25.4 mm

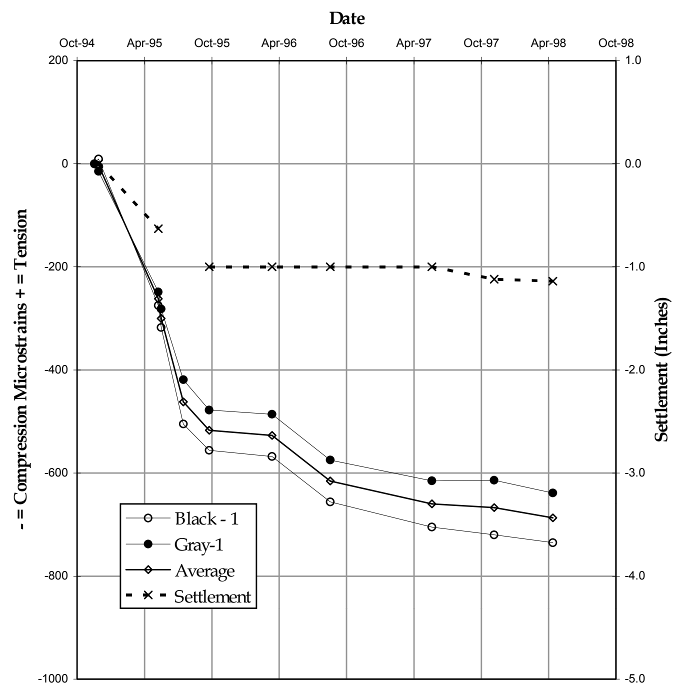

Fig. 3. Strain gage readings and measured settlement of Column B-6.

		CHANGE IN MICROSTRAINS			
	SETT.	GAGE	GAGE	GAGE	CONSTRUCTION
DATE	(in)	8745	8746	AVERAGE	ACTIVITY
3-Oct-94		0	0	0	No concrete in caissons
03-Oct-94		4	26	15	Fresh caisson concrete
10-Nov-94		24	50	37	Before cap poured
16-Nov-94		-25	80	28	After cap poured
19-Nov-94		53	20	37	Before column poured
30-Nov-94	0.00	93	14	54	After column poured
11-May-95	-0.63	142	-136	3	Eight floors poured
19-May-95		143	-154	-6	Starting to form 9th floor
18-Jul-95		149	-217	-34	Precast installed
26-Sep-95	-1.00	172	-284	-56	Windows installed
14-Mar-96	-1.00	169	-266	-49	Building completed
19-Aug-96	-1.00	162	-345	-92	Building completed
21-May-97	-1.00	158	-397	-120	Building completed
6-Nov-97	-1.12	161	-423	-131	Building completed
14-Apr-98	-1.14	148	-441	-147	Building completed

Note: Gage elevation is -21.5 feet (-6.5 m) Building Datum (BD)
1 inch = 25.4 mm

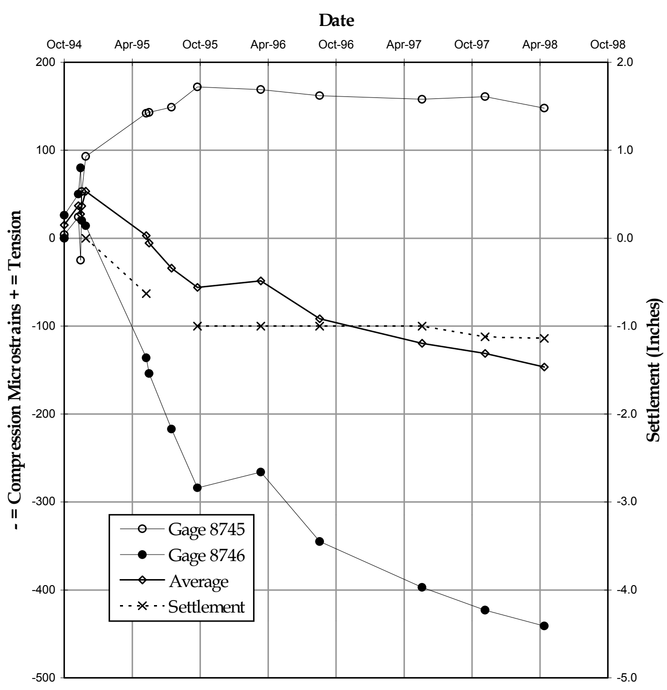

Fig. 4. Strain gage readings and measured settlement of Caisson B-6.

		CHANGE IN MICROSTRAINS			
DATE	SETT.	GAGE	GAGE	GAGE	CONSTRUCTION
	(in)	BLACK-2	GREY-2	AVERAGE	ACTIVITY
7-Nov-94	0.00	0	0	0	Before column was poured
16-Nov-94		18	114	66	After column was poured
30-Nov-94		31	123	77	No change
11-May-95		-294	-195	-245	Eight floors poured
19-May-95	-0.50	-338	-240	-289	Starting to form 9th floor
18-Jul-95		-489	-416	-453	Precast installed
26-Sep-95	-0.75	-535	-472	-504	Windows installed
14-Mar-96	-0.88	-547	-481	-514	Building completed
19-Aug-96	-0.88	-571	-532	-552	Building completed
21-May-97	-0.88	-583	-542	-563	Building completed
6-Nov-97	-0.95	-612	-604	-608	Building completed
14-Apr-98	-0.95	-607	-605	-606	Building completed

Note: 1 inch = 25.4 mm

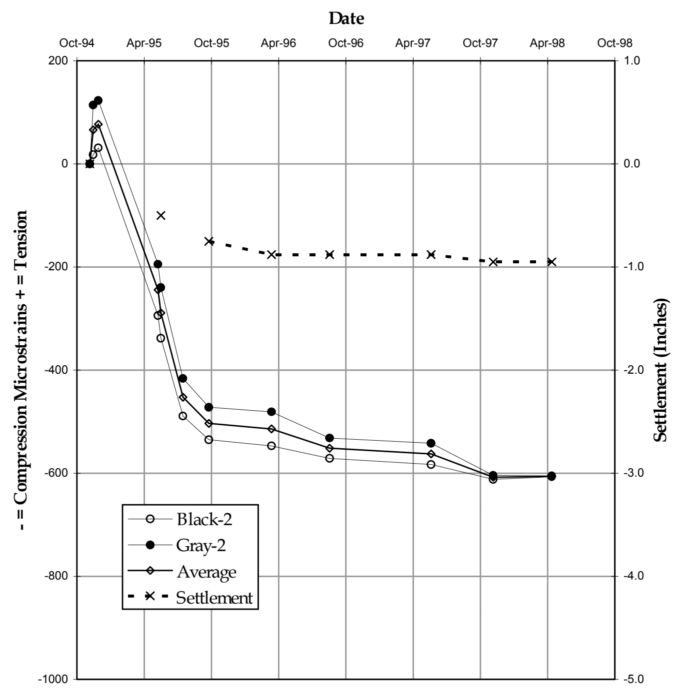

Fig. 5. Strain gage readings and measured settlement of Column C-2.

		CHANGE IN MICROSTRAINS			
DATE	SETT. (in)	GAGE 8747	GAGE 8748	GAGE AVERAGE	CONSTRUCTION ACTIVITY
3-Oct-94		0	0	0	No concrete in caissons
03-Oct-94		-23	2	-11	Fresh caisson concrete
01-Nov-94		-70	125	28	Before cap poured
07-Nov-94		-68	128	30	After cap poured
16-Nov-94		-49	130	41	Before column poured
30-Nov-94	0.00	-36	145	55	After column poured
11-May-95		-9	38	15	Eight floors poured
19-May-95	-0.50	-7	18	6	Starting to form 9th floor
18-Jul-95		1	-37	-18	Precast installed
26-Sep-95	-0.75	10	-79	-35	Windows installed
14-Mar-96	-0.88	2	-85	-42	Building completed
19-Aug-96	-0.88	-13	-116	-65	Building completed
21-May-97	-0.88	-37	-127	-82	Building completed
6-Nov-97	-0.91	-45	-149	-97	Building completed
14-Apr-98	-0.91	-53	-135	-94	Building completed

Note: Gage elevation is -26.3 feet (-8 m) Building Datum (BD)
1 inch = 25.4 mm

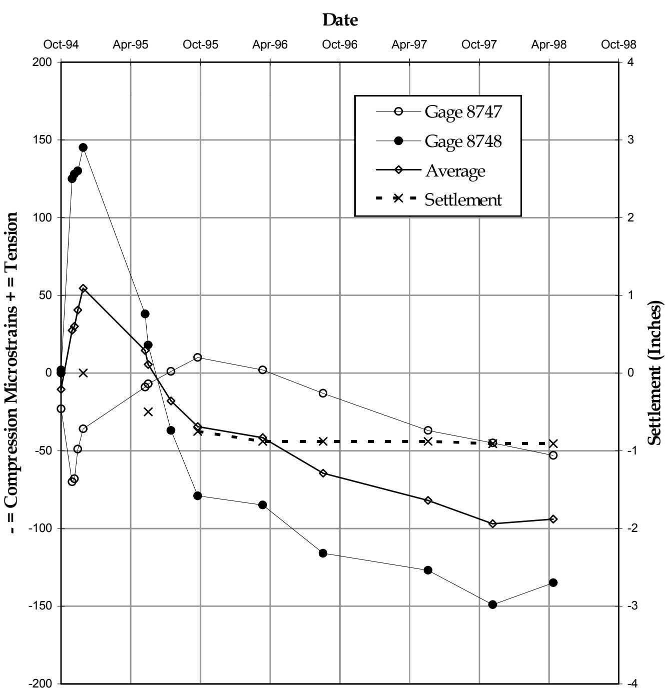

Fig. 6. Strain gage readings and measured settlement of Caisson C-2.

From the data obtained to date, it appears that the caissons are behaving slightly stiffer than anticipated and the ultimate settlement will be slightly less than predicted. It appears that the calculations for load sharing between footing and shaft based on the conservative modulus values below the shaft base (modulus values were reduced in half for possible loosening) over estimated the settlement. It would appear from the settlement data that no such loosening effect occurred and that a better correlation of prediction and performance would have been obtained by using the pressuremeter data without adjustment.

CONCLUSION

Innovative cost effective solutions to foundation design problems are sometimes possible using combinations or mixtures of foundation elements provided that ground deformation and response to structure loading can be reasonably predicted within allowable tolerances.

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